FINAL REPORT

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FINAL TECHNICAL REPORT
July 01, 1985 to February 28, 1989

INFRARED OBSERVATIONS OF THE SOLAR SYSTEM

INFRARED OBSERVATIONS OF THE SOLAR SYSTEM IN SUPPORT OF LARGE APERTURE INFRARED TELESCOPE [LARITS] : CALIBRATION

by

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The purpose of this project was to improve the infrared calibration base for infrared detectors. Groundbased infrared measurements of solid-surfaced planetary bodies, such as asteroids, are being used for the calibration of spacecraft detectors. A limitation has been the relatively poor theoretical understanding of thermal emission from these objects. The goal was to: (1) develop a database of ources and, (2) improve or modify the thermal models for these sources to provide a calibration data base for spacecraft infrared detector systems. The technique consisted of five phases: (1) design and construct infrared detector system to be used with and without collecting optics, (2) acquire whole-disk infrared lunar data relative to a laboratory blackbody and tie them to Mars (Venus or Mercury) and Vega, (3) compare with thermophysical models of the moon and modify, (4) acquire infrared asteroid photometry, (5) compare the lunar disk photometry with the asteroid calibrators using photometry and thermophysical models. The Si bolometer is calibrated without optics, attached to the portable telescope drive and Lunar disk measurements made. Next the bolometer is attached to the 90 inch telescope, Lunar scans are made and the remaining objects (planets, stars, asteroids) are measured.

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FINAL REPORT

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FINAL REPORT

AFOSR-TR- 0645

SUMMARY

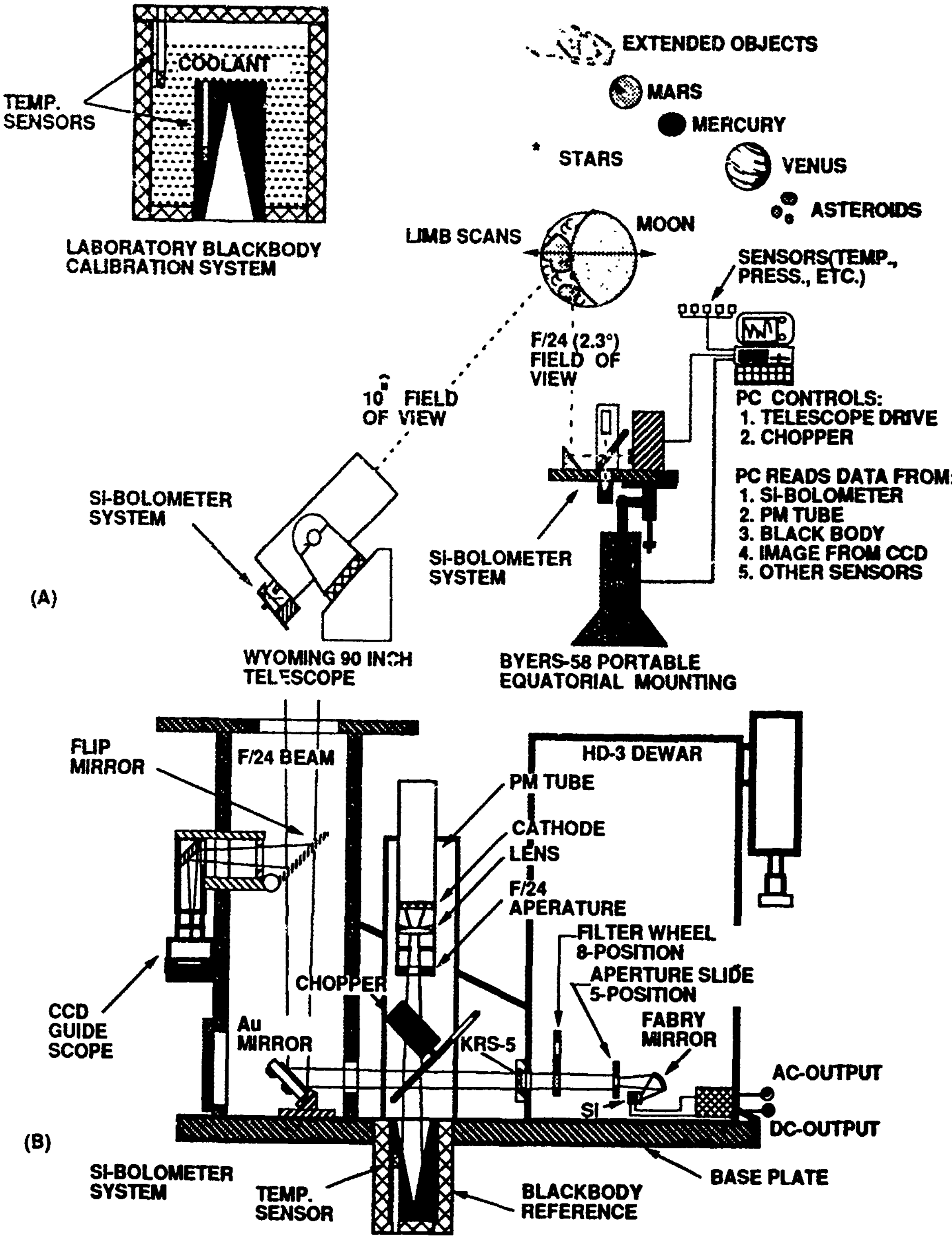
The Purpose of this project was to improve the infrared calibration base for infrared detectors. Groundbased infrared measurements of solid-surfaced planetary bodies, such as asteroids, are being used for the calibration of spacecraft detectors. A limitation has been the relatively poor theoretical understanding of thermal emission from these objects. The goal was to: (1) develop a database of sources and, (2) improve or modify the thermal models for these sources to provide a calibration data base for spacecraft infrared detector systems.

The technique consisted of five phases: (1) design and construct infrared detector system to be used with and without collecting optics, (2) acquire whole-disk infrared lunar data relative to a laboratory blackbody and tie them to Mars (Venus or Mercury) and Vega, (3) compare with thermophysical models of the moon and modify, (4) acquire infrared asteroid photometry, (5) compare the lunar disk photometry the asteroid calibrators using photometry and thermophysical models. The Si bolometer is calibrated without optics, attached to the portable telescope drive and Lunar disk measurements made. Next the bolometer is attached to the 90 inch telescope, Lunar scans are made and the remaining objects (planets, stars, asteroids) are measured. — RH4

An infrared Si bolometer system was purchased, a unique mounting system designed and built to use with a portable drive and the 90-inch telescope without changing in the optical arrangement. The bolometer has 5-apertures, 8-filter positions, AC and DC outputs. The AC drive motors of the portable telescope were replaced with stepper motors so that setting and tracking can be controlled with an IBM PC. Simultaneous visible measurements were obtained. Thermal modeling for a smooth rotating sphere with arbitrary illumination angle, sun distance and thermophysical properties was developed to determine infrared emission spectrum. Cratering was included by considering low albedo spots on the surface of a solid planetary body. Our zero order model is analogous to craters since low albedo spots tended to absorb light more efficiently than the smooth environs This explains the non-blackbody behavior of the Galilean satellites and some asteroids. The model is sufficiently flexible to include craters in sizes from a few millimeters to craters on the order of 10's of kilometers, thus accounting for the shadowing effect caused by these surface irregularities. Next the surface roughness was modeled as paraboloidal holes [craters] of specific depth to diameter ratio. Multiple scattering of incident solar radiation and the re-emitted thermal radiation inside the crater and directional emissivity were included. Engineering tests were carried out at the Observatory during November and December, 1987. A series of observations were planned during 1988 and 1989, however, consistent bad weather conditions prevented obtaining any data. A paper was presented at the 19 th Annual DPS of the American Astronomical Society meeting November 19-13, 1987, Pasadena, California "Infrared Calibration From High Resolution Planetary and Lunar Measurements." A theoretical paper was presented at the 19 th Lunar and Planetary Science meeting, NASA-Johnson Space Center, Houston Texas, March 14-18, 1987, "Improved Thermal Models Solid Planetary Bodies." A paper was written " Modeling the Non-Gray-Body Thermal Thermal Emission from the Full Moon" and is being reviewed by *Icarus*.

AFOSR-85-0181

INFRARED OBSERVATIONS OF THE SOLAR SYSTEM: CALIBRATION



Experimental approach is shown in (A). Note that there is no change in the optics when the "Si-Bolometer System" is placed on the Wyoming 90" telescope. Details of the "Si-Bolometer System" are shown in (B).

1.0 INTRODUCTION

The purpose of this research project was to obtain an improved calibration base for spacecraft infrared detectors and to understand the thermophysical properties of asteroids. The uniqueness of this project is that we will tie together, with thermal models, infrared photometry of potential asteroid calibrators, the moon (an asteroid "prototype"), and standard stars, taken with the *same instrumentation*. These asteroids could then be used as infrared flux calibrators.

The moon, asteroids, planets, satellites and stellar sources are used for infrared calibration of groundbased as well as spacecraft detectors. Two colleagues, Dr. Paul Johnson (University of Wyoming) and Dr. Thomas Greene (Boeing Aerospace Company), and I are pursuing a program for improving infrared calibration for both groundbased and spacecraft detectors by the study of thermal emission from the moon and asteroids.

The requirements for a class-A Silicon Bolometer were developed in cooperation with Infrared Laboratories, Incorporated of Tucson, Arizona. Calibration and observing methods were developed. A chopper system and an automated telescope drive system were designed. A phase-lock-loop chopper controller was built and tested. The base plate which holds the Bolometer, blackbody, photomultiplier tube, chopper, etc. was designed and built. The base plate was used for attaching the detector system to the WIRO 90-inch telescope and to the Byers - 58 German equatorial mounting. An improvement to the traditional thermal model was developed.

2.0 OBJECTIVES

The objective of this project was to improve the infrared calibration base for infrared detectors. Groundbased infrared measurements of solid-surfaced planetary bodies, such as asteroids, are being used for the calibration of spacecraft detectors, on IRAS for example, and are being considered on other systems. A limitation has been the fact that these objects are not theoretically well understood. It is, therefore, the goal of this research to: (1) develop an improved database of these infrared sources and, (2) improve or modify the related thermal models for these various sources in order to provide a calibration data base for spacecraft infrared detector systems.

3.0 WORK PLAN

3.1 First Year

The work plan carried out for the first year are shown in chart form. The first year Work Plan is summarized in TABLE 3.1-1. During the first three months it was determined that a study of the automatic telescope control system should be made earlier in the program then originally planned. This was because the bolometer design would determine the platform design. During the next 3-months the main problem uncovered was how best to tie together the whole disk IR measurements of the Moon made using the F/24 beam (1.2° resolution) of the bolometer without external optics (no telescope) with those made using the telescope (10 arc seconds resolution). The IR measurements made with the telescope will include asteroids, Mars, stars, etc. Mars seems to be the best object to tie the measurements together so that asteroids can be used as IR-calibrators. This problem, however, was still under study. During the last half of the first year the Bolometer was be delivered and testing of the dewar was done. The chopper, blackbody and the mounting plate were be built. It was planned to make the first observations during the last two months of the first year. Some of the thermal models were modified to compare and calibrate the lunar disk measurements at different phases with that of Mars. During March and April 1986 a detailed plan for the second year was be developed.The first year was within budget and met our goals.

3.2 Second Year

The Work Plan for the second year also had some revisions which are indicated in the revision column with an "®" in TABLE 3.2-1. Items completed are marked with "◊". The observing schedule has been delayed about four months because the base plate required longer for construction than initially planed. The delivery of the photomultiplier tube and mu-metal shield also require longer lead time than estimated. We had no other major delays the remainder of the second year. The budget remained within the amount granted.

3.3 Third Year

The third year Work Plan is summarized in TABLE 3.3-1 and had several revisions reflecting the delays mentioned above. We expect to carry out the project on time and within the planned budget.

TABLE 3.1-1 WORK PLAN RJULY OI 1985 TO JUNE 30, 1986

#	ITEM / MONTH AFTER START-UP	REV.	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	#	
1	Review Work Plan	®	•◊													1	◊
2	Planning meet./SLC:RWS,PEJ	®	•◊													2	◊
3	Order #1 detector/ dewar system	®									•◊					3	◊
4	Design mounting plates	®						•◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊				4	◊
5	Design chopper	®		•◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊								5	◊
6	Design blackbody	®				•◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊		6	◊
7	Develop calibration plan for dewar	®												•◊◊◊◊◊	◊◊◊◊◊◊	7	◊
8	Plan observing strategy	®			•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊•					8	◊
9	Start graduate student on project		•◊													9	◊
10	Build mounting plate	®														10	◊
11	Preliminary testing of dewar	®														11	◊
12	Build Chopper	®					•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊		12	◊
13	Test Chopper	®									•◊◊◊◊◊	◊◊◊◊◊◊				13	◊
14	Review thermal models	®						•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	14	◊
15	Modify thermal models										•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	15	◊
16	Engineering test run on 90-inch	®														16	◊
17	Observe(M) Moon /(A)Asteroids	®														17	◊
18	Study Automated Drive Systems	®	•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊						◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊			18	◊
19	Review Results of Automated Study	®			•◊◊◊◊◊										◊◊◊◊◊◊	19	◊
20																20	
21																21	
22																22	
23																23	
24																24	
25																25	
26																26	
27																27	
28	Develop second year plan details	®						•◊			•◊◊◊◊◊◊					28	◊
29	Submit 2nd Year Plan	®						•◊								29	◊
30	Status review/SLC:RWS,PEJ	®							•◊			•◊				30	◊
31	Technical Society Meeting															31	
32	Written status reports							•◊◊◊◊			•◊					32	◊
33	STARTED JULY 1, 1985		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	1986	◊
Y	Notes: •=Start/end; ®=Revised; ◊=Completed		◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊		

FIRST YEAR ACTIVITY

TABLE 3.2-1 WORK PLAN 01 JULY 1986TO JUNE 30, 1987

#	ITEM / MONTH AFTER START-UP		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	#	
1	Review second year Work Plan		•◊												1	◊
2	Planning meet./LAR:RWS,PEJ,TFG		•◊												2	◊
3	Order telescope drive system	®				•◊									3	◊
4	Design new mounting plate	®			•◊										4	◊
5	Modify chopper design	®				•◊◊◊◊◊◊•									5	◊
6	Modify blackbody design	®			•◊◊◊◊◊•										6	◊
7	Review calibration plan for dewar	®					•◊◊◊◊◊◊•								7	◊
8	Plan new observing strategy					•◊◊◊◊◊◊◊◊◊•									8	◊
9	Review graduate student's work		•◊												9	◊
10	Modify mounting plate	®				•◊◊◊◊◊•									10	◊
11	Preliminary test of drive system	®								•◊◊◊◊◊•					11	◊
12	Review meeting/LAR:RWS,PEJ,TFG								•◊						12	◊
13	Modify chopper				•◊◊◊•										13	◊
14	Modify blackbody standard				•◊◊◊◊◊◊◊•										14	◊
15	Review current thermal models				•◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊•										15	◊
16	Modify thermal models							•◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊◊•							16	◊
17	Engineering test run on 90-inch						•◊	•◊							17	◊
18	Observe(M) Moon /(A)Asteroids	®					M◊◊			A	M	A	M	A	18	
19															19	
20															20	
21															21	
22															22	
27															27	
28															28	
29															29	
30															30	
31															31	
32	Develop third year plan details												•◊◊◊◊◊◊◊◊◊◊◊◊◊◊		32	◊
33	Status review/SLC:RWS,PEJ				•◊			•◊							33	◊
34	Data review/SLC:RWS,PEJ												•◊		34	◊
35	Technical Society Meeting											•◊			35	◊
36	Written status reports				•◊						•◊			•◊	36	◊
37	STARTED JULY 1, 1986		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	37	
Y	Notes: •=Start/end; ®=Revised; %=Completed														Y	

SECOND YEAR ACTIVITY

TABLE 3.3-1 WORK PLAN 01 JULY 1987 TO 30 JUNE 1988

#	ITEM /MONTH AFTER START-UP		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	#	
1	Review third year Work Plan		•◊•													1	◊
2	Planning meet./LAR:RWS,PEJ,TFG		•◊													2	◊
3	Order #2 detector/dewar system		•◊													3	◊
4	Design new mounting plate		•◊◊◊◊	◊◊•												4	◊
5	Modify chopper design if needed			•◊◊•												5	◊
6	Modify blackbody design if needed	®		•◊◊	◊◊◊◊◊	•										6	◊
7	Review calibration plan for dewar				•◊◊◊•											7	◊
8	Plan observing strategy					•◊◊◊◊◊	◊◊◊◊◊•									8	◊
9	Review graduate student's work		•◊													9	◊
10	Modify mounting plate if required			•◊◊◊	◊◊◊◊◊◊											10	◊
11	Preliminary test dewar system	®				•◊◊◊◊◊	◊◊◊◊◊◊	◊◊•								11	◊
12	Review meeting/LAR:RWS,PEJ,TFG								•◊							12	◊
13	Modify chopper if required				•◊◊◊◊	◊•										13	◊
14	Modify blackbody if required				•◊◊◊◊	◊◊◊◊◊•										14	◊
15	Review current thermal models		•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	15	◊
16	Modify thermal models					•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	16	◊
17	Engineering test run on 90-inch						•◊	•								17	
18	Observe(M) Moon /(A)Asteroids	®			M	A	M	A	M	A	M◊◊◊	A	M	A		18	
19	Develop final calibration list	®								•					•	19	
20																20	
21																21	
22																22	
23																23	
24																24	
25																25	
26																26	
27																27	
28	Status review/SLC:RWS,PEJ				•◊											28	◊
29	Data review/SLC:RWS,PEJ												•◊			29	◊
30	Technical Society Meeting								•◊							30	◊
31	Final report	®														31	
32	Written status reports				•◊			•◊			•◊			•◊		32	◊
33	START JULY 1,1987		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	33	
	Notes: •=Start/end; ®=Revised; ◊=Completed																

THIRD YEAR ACTIVITY

3.4 Fourth Year

The fourth year Work Plan is summarized in TABLE 3.4-1 and had revisions reflecting the delays mentioned above. The observing weather was bad and observations were not made. We expect to carry out most of project on time and within the planned budget.

3.5 Future Years

Further observations will be made after the contract is completed through other funding sources. The theoretical work will be carried out as part of a Ph. D. thesis at the University of Wyoming during 1989 to 1991.

4.0 ACTIVITIES

4.1 Equipment

4.1.1 Silicon Bolometer

Whole disk measurements of the moon are made without optics. The detector system, therefore, had to have a uniform response over the f/24 detected beam. This required a special design of the internal bolometer optics so that the detector system could also be mounted on the Wyoming f/23.5 IR telescope to observe smaller objects. When mounted on the Wyoming IR telescope the resulting design will give us resolution of 4, 10, 16 and 23 arc seconds. It was determined that with the aperture sizes we plan to use diffraction was not significant at the wave lengths of interest. A silicon bolometer detector system was constructed by the Infrared Laboratories,Inc. to meet our requirements as listed below:

A) Bolometer (HD-3 Helium dewar):	
1. Material:	Silicon
2. Area:	1.05mm x 1.20mm
3. Operating Temperature.:	1.5°K
4. Frequency Response (70%):	115Hz
5. Thermal Conductivity (G):	~ 1μW /°K
6. Responsivity:	2.2×10^{6} V/W
7. N.E.P.:	2.2×10^{14} W/Hz$^{1/2}$
8. Window:	2mm KRS-5
B) Fabry Mirror	
1. Shape:	Off-axis Paraboloid @ F/24
2. Original Paraboloid size:	25.4mm
3. Radius of curvature:	50.80mm at Paraboloid original center
4. Focal length of Paraboloid:	25.40mm
5. Focal length of off-center Paraboloid:	11.40mm
6. Off-center distance:	7.00mm

TABLE 3.4-1 WORK PLAN 01 JULY 1988 TO 28 FEBRUARY 1989

#	ITEM /MONTH AFTER START-UP		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	#	
1	Review FOURTH year Work Plan		•◊•													1	◊
2	Planning meet./LAR:RWS,PEJ,TFG		•◊													2	◊
3	Order #2 detector/dewar system		•◊													3	◊
4	Design new mounting plate															4	◊
5	Modify chopper design if needed	®				•◊◊•										5	◊
6	Modify blackbody design if needed	®		•◊◊•												6	◊
7	Review calibration plan for dewar	®					•◊◊◊•									7	◊
8	Plan observing strategy	®	•◊◊◊◊◊	◊◊◊◊◊•												8	◊
9	Review graduate student's work	®	•◊													9	◊
10	Modify mounting plate if required															10	◊
11	Preliminary test dewar system															11	◊
12	Review meeting/LAR:RWS,PEJ,TFG					•◊										12	◊
13	Modify chopper if required															13	◊
14	Modify blackbody if required															14	◊
15	Review current thermal models		•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊						15	◊
16	Modify thermal models					•◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊	◊◊◊◊◊◊						16	◊
17	Engineering test run on 90-inch															17	
18	Observe(M) Moon /(A)Asteroids	®			M	A	M	A	M	A						18	
19	Develop final calibration list	®								•___•						19	
20																20	
21																21	
22																22	
23																23	
24																24	
25																25	
26																26	
27	END OF CONTRACT									◆◆◆						27	
28	Status review/SLC:RWS,PEJ				•◊											28	◊
29	Data review/SLC:RWS,PEJ															29	◊
30	Technical Society Meeting										•◊					30	◊
31	Final report	®								•____	____	____	____	____	____	31	
32	Written status reports	®			•◊											32	◊
33	START JULY 1,1988		JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	33	
	Notes: •=Start/end; ®=Revised; ◊=Completed																

FOURTH YEAR ACTIVITY

7. Field Stop to Mirror:	30mm (not critical)
8. Geometrical spot size:	1.06mm
9. Electronics:	LN-6/C preamplifier
C) Aperture Slide	
1. Positions:	5
2. Openings:	Blank,2.0mm, 3.0mm, 5.0mm, 10mm
D) Filter Wheel	
1. Positions:	8
2. Drive: Stepper motor	
3. Filters position 1:	2.28μ/HBW0.47μ(6mm thruaperture)
position 2:	5.03μ/BW0.89μ (6mm thru aperture)
position 3:	8.4μ (3mm thru aperture)
position 4:	11.5μ (3mm thru aperture)
position 5:	Blank
position 6,7,8:	Open

A photograph of the Bolometer with the telescope attachment is shown in Figure 4.1.1-1. The blackbody will be a re-entrant cone type. Both reference and calibration blackbody will be identical except for the coolant fluid that surrounds the calibration blackbody. The blackbody is shown in Figure 4.1.1-2. The major components of the infrared detector system have been assembled and the optics aligned . The major system components include the bolometer/dewar, chopper, reference black bodies, temperature sensing system, mounting "boot", and the various drive motors and controllers. Work completed on the system is divided into two areas: laboratory testing of the bolometer/dewar, and design and construction of the temperature sensing system for monitoring the reference black bodies (see Figure 4.1.1-3).

Figure 4.1.1-1 Si-Bolometer with the telescope attachment (boot).

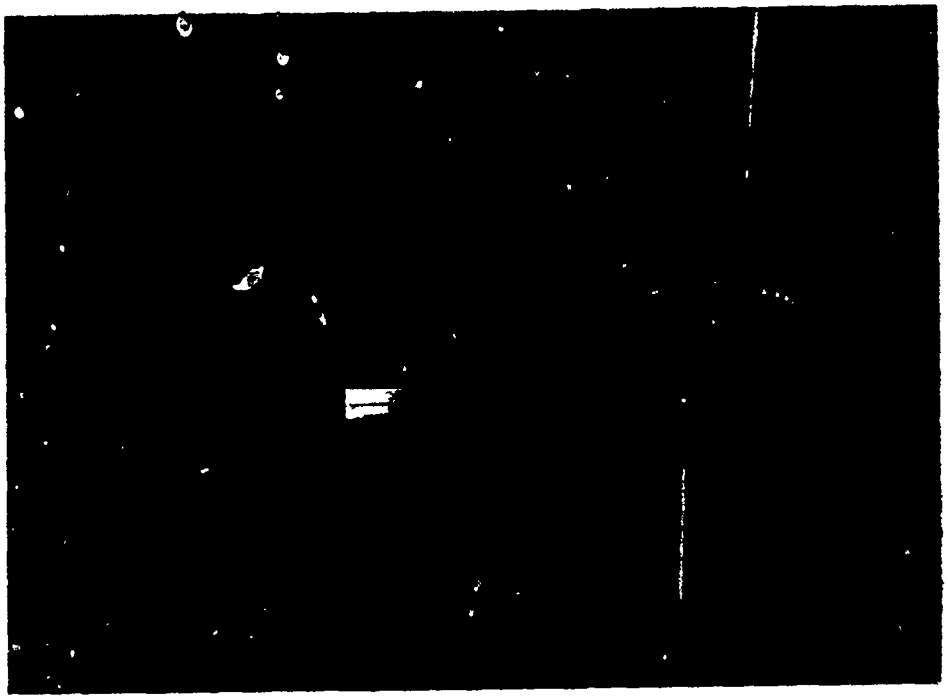


Figure 4.1.1-2 Blackbody arrangement.

Figure 4.1.1-3 Temperature sensing system (RTD) for monitoring the reference blackbody.

The initial laboratory tests on the bolometer/dewar were done to determine the quality of vacuum in the dewar and the hold time for liquid nitrogen and liquid helium. The dewar was evacuated using conventional mechanical and diffusion pumps. Typically the dewar is at $\leq 5 \times 10^{-7}$ torr after it is removed from the diffusion pump. The nitrogen/helium "can" (see Figure 4.4.4-4will hold 0.8 liters of liquid helium and has a hold time approaching 20 hours. At the operating temperature of 1.6°K (corresponding to about 10 torr), helium is blown off at the rate of 1.6 liters/min, giving a hold time of about 15 hours.

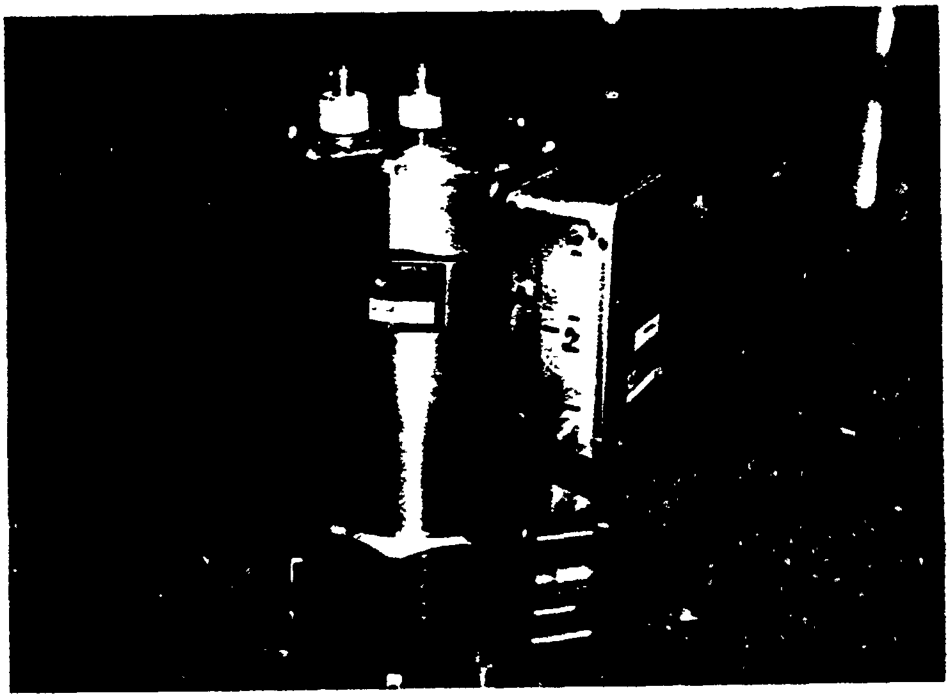


Figure 4.1.1-4 The Si-Bolometer Dewar

The dark noise of the detector was measured to be $\leq 3.3 \times 10^{-9}$ V Hz$^{-1/2}$ at 20 Hz and $\leq 3.16 \times 10^{-9}$ V Hz$^{-1/2}$ at 40 Hz, which is within the specifications supplied by Infrared Laboratories, Inc. Other tests of the detector were conducted when the instrument was not on the telescope and the laboratory facilities were available.

4.1.2 Chopper

A four bladed chopper blade was obtained from Boston Electronics. This blade was cleaned and coated with aluminum at the University of Wyoming. Both sides were coated so that a visible photomultiplier could be used along with an IR detector. The electronics for a phase-lock-loop system were designed to operate at a frequency of 10-20 Hz. A breadboard

model was built and tested. An LCD provides a continuous frequency readout. A description of the chopper study is given in Appendices 5.1.

4.2 Telescope Drive

Fundamental differences exist between the two general types of automated telescope drives. The selection of either of DC motor driven system or the stepper motor type influences the other choices that must be made, i.e. open or closed loop, equatorial or altitude/azimuth, mount, etc.

DC Motor Drive

Using DC motors to position the telescope requires a closed-loop type system, probably employing inexpensive potentiometers as shaft encoders. DC motors probably are not suitable for smooth tacking. A literature search indicates that either steppers or 60 Hz synchronous motors are required for tracking. This means that the DC motors would be used for positioning, and a third motor would take over for tracking. Of course, if a certain amount of jitter can be tolerated, a separate tracking motor would not be necessary.

The advantage of an IBM PC board for controlling DC motors is that it controls the ramping of the motor, but it may be expensive. It would not be too difficult to build such a control. In building one it is necessary to worry about the mechanics of such a system (damping, etc.). This system would require an equatorial mount if a separate tracking motor became necessary.

Stepper Motor Drive

Stepper motors are suitable for positioning and tracking, and are accurate in an open loop system. Several stepper control board for the PC are available, along with software to control ramping etc. Another approach is to use an "intelligent" stepper control chip. A programmable chip that generates control pulses, determines ramping profiles and total number of steps. A board for the PC could be made using two such chips (one for each axis) and would greatly simplify the software. It also frees the CPU for other functions.

Another possibility would be to adapt the stepper control circuit used by the University of Utah Physics Department for their telescope, for use with the PC. It is also possible to control a stepper with pulses generated directly from software. This may be difficult to do in BASIC. A language such as FORTH may be more suited to the task. Steppers are suitable for either equatorial of altitude/azimuth mounts.

The Edwards R. Byers Co. is currently constructing for us a BYERS-58 German Equatorial Mounting. It was completed by the early part of February 1987. They retrofited Hurst stepping motors at a very minimal cost. It was decided that stepper motors were more suitable for positioning and tracking, and are accurate in an open loop system. Two control boards and a D/A board for the IBM PC were also available at a reasonable cost. These boards met all the tracking and setting requirements.

4.3 Measurements

The assembled detector system has been tested in the laboratory and was first mounted on the Wyoming 2.3m telescope during our November 3-5, 1987 observing run. Two nights during this run were spent debugging the instrument. A third night was lost due to inclement weather. A second observing run is scheduled for mid-December 1987. The calibration observations measurements will be carried out on the Wyoming telescope January thru June 1988. The calibration observations measurements with bolometer alone (no optics) will be carried out on the Byers drive At the University of Wyoming.

The major components of the infrared detector system were assembled and the optics aligned (see Figure 4.3-1). The major system components include the bolometer/dewar, chopper, reference black bodies, temperature sensing system, mounting "boot", and the various drive motors and controllers. Work completed on the system is divided into two areas: laboratory testing of the bolometer/dewar, and design and construction of the temperature sensing system for monitoring the reference black bodies. The assembled detector system was tested in the laboratory and was first mounted on the Wyoming 2.3m telescope during our November 3-5, 1987 observing run. Two nights during this run we spent debugging the instrument. A third night was lost due to inclement weather. A second observing run is scheduled for mid-December 1987. An oral report discussing the state of the instrument was presented at the 19 th Annual DPS meeting held in Pasadena, California on November 9-13, 1987.

A major portion of the second summer was spent on the design and construction of the temperature sensing system needed to accurately monitor the reference black bodies. After consulting the literature on temperature measurement and calibration, it was decided that an application of platinum resistance thermometry would give the required accuracy and precision. We use thin film platinum resistance temperature detectors (RTD's have very small self heating errors and conform rigorously to international standards established for the relation between resistance and temperature.

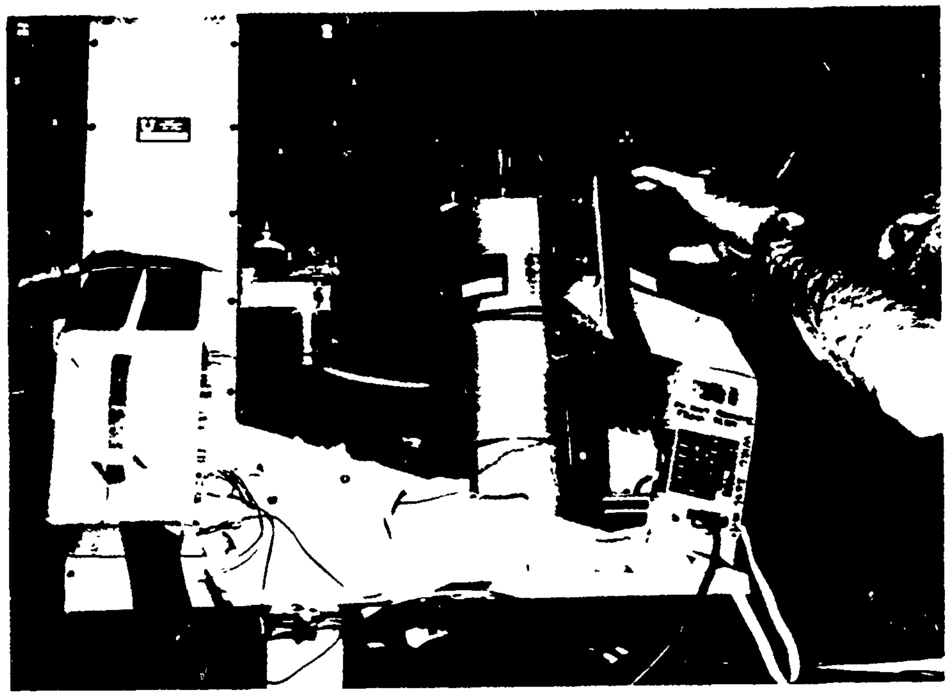


Figure 4.3-1 Major componets

The method used to obtain the detector resistance is referred to as the four wire technique. In this approach, a number of RTD's (see Appendicies 5.7) are connected in series with a high precision, low temperature coefficient resistor. A constant current source supplies the current needed to activate the detectors. The voltage across each sensor and the "known" resistor are measured using a digital voltmeter or similar devise. The current is computed using the value of the "known" resistor.

The detector resistance is then calculated using Ohm's law. To make these measurements we use an ADC-1 manufactured by Remote Measurement Systems Inc. The ADC-1 is a 12 bit differential analog to digital converter/RS232 serial communications interface. An IBM PC records the voltages and makes the necessary calculations to determine the temperature and flux of the reference black bodies. Referring to Figure 4.3-2, we see the circuit design allows the use of up to seven RTD elements. The design leaves eight free analog inputs which will allow the addition of other sensors (pressure, humidity, etc.) in the future. The current system is capable of $\pm$ 0.1°C accuracy over a temperature range of -40°C to +40°C. Calibration is done using a water/ice bath which, when properly prepared, is at 0°C $\pm$ .002°C. Calculations indi-

cate that at 10μ an error of ±0.1°C results in $\Delta F/F = 0.16\%$ at 300°K where F is the black body flux and ΔF is the propagated error. Data on the various circuit components follows Figure 3.

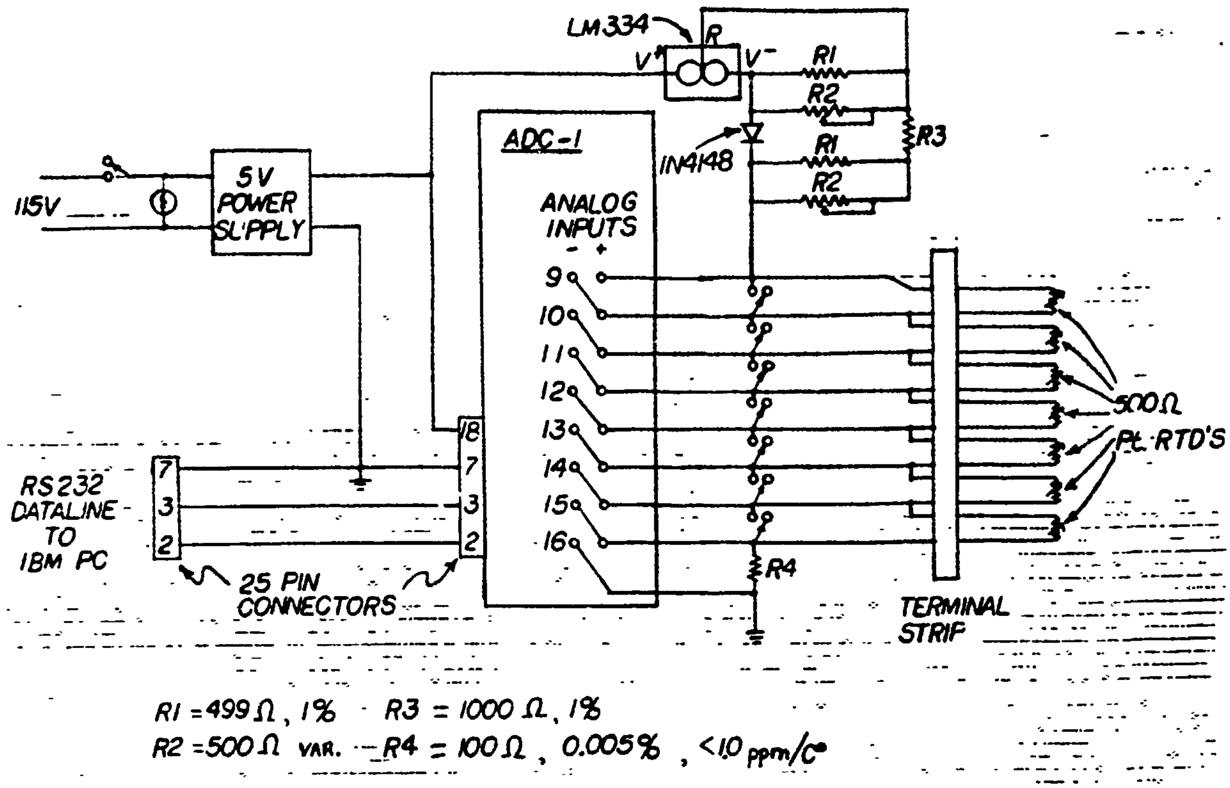


Figure 4.3-2 Circuit design of a seven RTD elements.

4.4 Thermal Studies

During the first year we finished the thermal modeling for a smooth rotating sphere with arbitrary illumination of viewing angle, distance from the sun and thermophysical properties to determine the spectrum of its infrared emission. We further enhanced the model by modeling cratering to consider low albedo spots on the surface of a solid planetary body. This is a zero order model analogous to craters since the low albedo spots tended to absorb light more efficiently than the smooth surrounding plains. This explains to some extent, the non-blackbody behavior of some asteroids and the Galilean satellites which have non-graybody spectra. Currently we are further improving the model by using actual crater shapes. The improved model takes a single crater assumed to be parabolic in shape with a certain depth to diameter ratio located at an arbitrary latitude and longitude on a body with an arbitrary polar orientation.

This crater is taken through a diurnal cycle and viewed at some arbitrary angle to model the infrared flux as seen by the observer. The crater is considered in terms of the heat flow, foreshortening effects, areas seen and not seen by the observer, areas illuminated and not illuminated, etc. The next step will be to compare the diurnal flux curve and infrared spectra of this crater with flat plains. Finally, we will take the code and incorporate it into a spherical solid surface planet model where these craters, with a given depth to diameter ratio, cover a certain percentage of the the surface. Our improved model is based in part on the following three papers concerning the visible photometric function· (1) Icarus, Vol. 64, p.320-328,1985; "Photometry of Rough Planetary Surfaces: the Role of Multiple Scattering", Bonnie J. Buratti and Joesph Veverka, (2) Icarus, Vol. 19, p. 542-546, 1973; "The Effects of Scattering and Conduction on Radiative Transfer in Lunar and Mercurian Surfaces", J. Srinivasan and R. T. Ceff; (3) Ann. Acad. Sci. Fenn. Ser. A. No. 172, 1965, "The Shadow effect on Phase Curves of Lunar Type Surfaces ", K. A. Hameen-Antilla, P. Laasko and K.Lumme.

We have improved our thermal models of solid-surfaced planets to include the effects of negative topography. Matson et al. ,(1983) have plotted the brightness temperature of the Galilean satellites decreases by -0.5°K/micron from 8.0 to 14.0 microns whereas a non-rotating sphere model gives a slope of only -0.25°K/micron. Matson has shown that color calibration errors and wavelength dependent emissivity will not explain the observations. Murcray's (1965) 6-12 micron data tor the Moon and Voyager IRIS 30-50 micron data for Ganymede show this same effect.

The observed decrease in brightness temperature with wavelength cannot be explained by positive relief,because this would have the opposite effect. Mountains on the terminator would allow sunlight to strike more nearly normal to the local surface. This would beam light back toward the sun, boosting energy at longer wavelengths.

One possible explanation is negative relief. Negative topography would produce areas of higher brightness temperature, especially near the subsolar point. This enhances short-wavelength radiation, producing a fall-off in brightness temperature with wavelength. This occurs because crater floors have higher temperatures than plains. This happens because: 1) they see sunlight reflected from crater walls as well as duect sunlight, and 2) they radiate into less than 2π steradians of sky.

We have produced a preliminary model of negative relief with a two-albedo "golf ball" model. Craters are modeled as a uniform distribution of low-albedo crater floors. Although

crater floors don't necessarily have lower albedos than the surroundings, a low *effective* albedo gives them the desired temperature enhancement in our model. Only two additional parameters are needed in our standard thermal model: 1) the percentage of the sphere covered with crater floor, and 2) the effective albedo of the floor.

We have modeled the brightness temperatures of the moon and Europa with our model and plotted them against observations (Figures. 4.4-1 and 4.4-2). The data agree well for Europa and

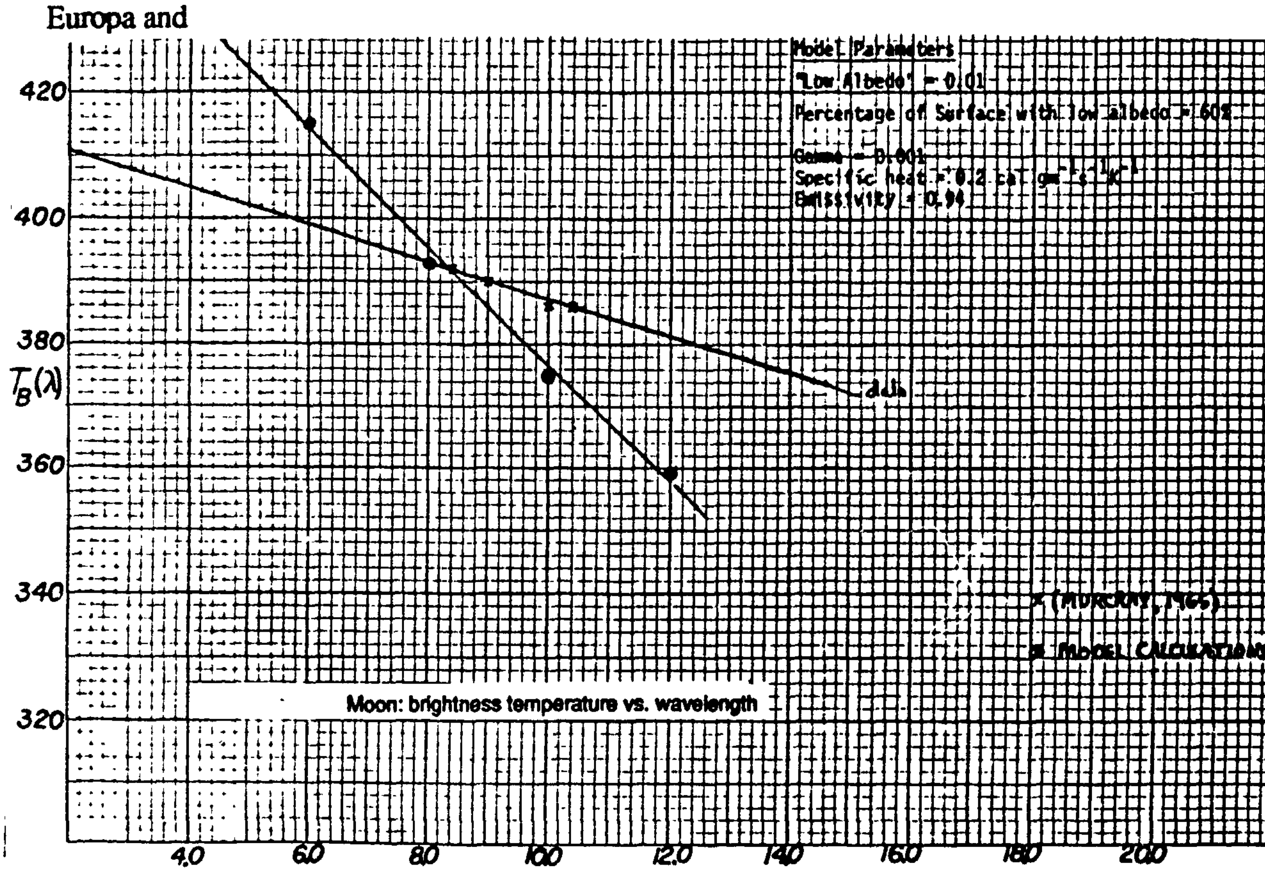


Figure 4.4-1 Moon brightness temperature vs. wave length

actually produce a *steeper* curve for the Moon than is observed. An additional improvement needed for the model is to decrease the percentage of low-albedo material viewed at the limbs, where crater floors are hidden from view. This requires one additional parameter. We also need to apply the following constraints to better determine the three negative relief model parameters: 1) the observed infrared limb-darkening of the Moon, 2) the observed brightness temperature of crater floors on the moon, and 3) detailed theoretical models of illumination and emission from a crater.

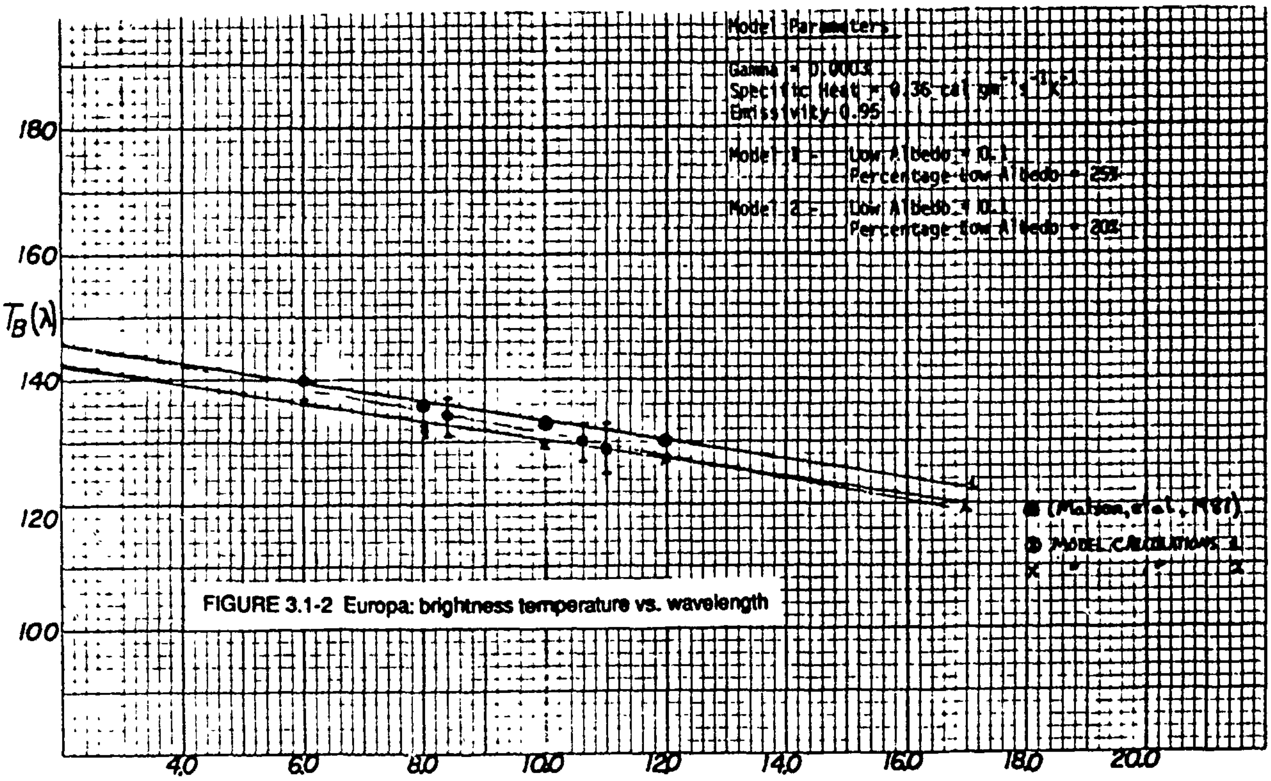


Figure 4.4-2 Europa brightness temperature vs. wave length

We are currently working on a more detailed theoretical model of illumination and emission from a crater. This model should be sufficiently flexible so as to include craters ranging in size from a few millimeters to large craters on the order of 10s of kilometers, thus accounting for the shadowing effect caused by these surface irregularities. Hameen-Anttila et al.,(1965), suggest that the depth to diameter ratio is a more important factor in characterizing surface roughness than is the actual shape of the depression. The albedo of the surface is the other important model parameter, and is assumed to be the same throughout the crater and its immediate neighborhood. The current theoretical model is based on the parabolic hole model of Hameen-Anttila et al., (1965). The geometrical model allows us to describe the details of crater illumination so that we can solve a 1-dimensional heat flow equation for an arbitrary point on the crater surface. From the resulting temperature map we hope to calculate the emergent flux as compared to the incident flux so as to better understand emission from craters.

<u>Model Geometry</u>. Following Hameen-Anttila et al., (1965) we assume that craters are parabolic holes with a specifiable depth to diameter relation. Figure 4.4-3 shows the geometry for a crater of radius **R** and depth h at an arbitrary point **P**. on a planetary surface. Given the coordinate system in the diagram, the crater is described by the paraboloid:

$$Z = \begin{cases} h/R^2(\ x^2 + y^2) - h & ;\ x^2 + y^2 \leq R^2 \\ 0 & ;\ x^2 + y^2 > R^2 \end{cases}$$

Analysis of the viewing geometry leads to the following mathematical description of the crater. Here,

$$x^2 + y^2 \leq R^2 \tag{1}$$

specifies that a point is inside the crater. Then,

$$\{\ x^2 - R^2/h\ \ \cot\ e\ \}^2 + y^2 \geq R^2 \tag{2}$$

specifies that a point inside the crater is visible to the observer. The following equation specifies whether or not a given point in the crater is illuminated,

$$\{\ x - R^2/h\ \ \cos\ A\ \cot\ i\ \}^2 + \{\ y - R^2/h\ \ \sin\ A\ \cot\ i\ \}^2 \geq R^2 \tag{3}$$

$$0 \leq A \leq 180°$$

The unit normal at an arbitrary point on the crater surface is,

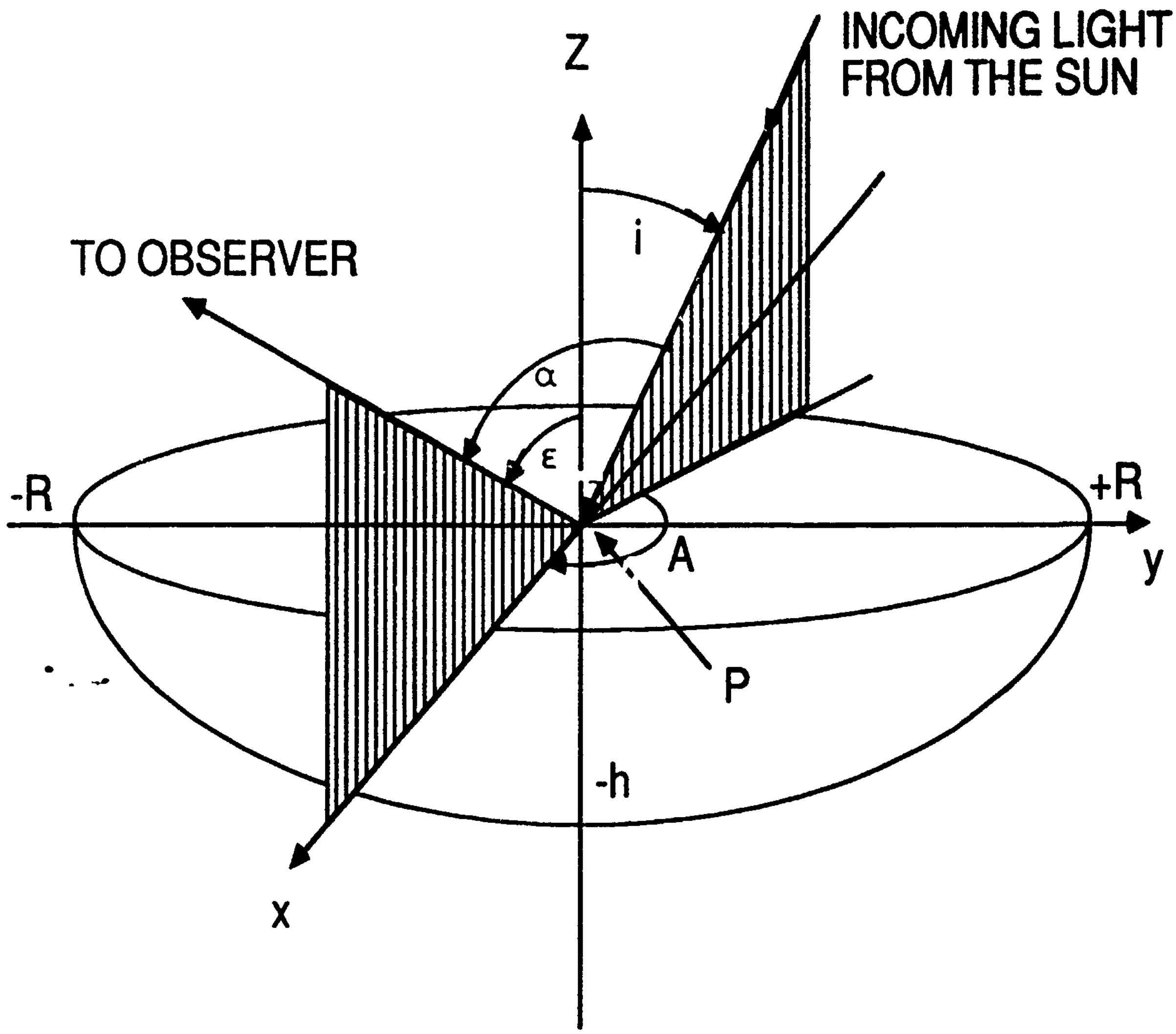
$$\bar{n} = \frac{\{[-2h\ /\ R^2]\ x\ ,\ [-2h\ /\ R^2]y\ ,\ 1\}}{\{\ 1 + [4h^2\ /\ R^2]\ (x^2 + y^2)\}^{1/2}} \tag{4}$$

Using the unit vectors toward the earth and the sun,

$$\bar{n}_E = \{\ \sin\ e,\ 0,\ \cos\ e\ \}$$

$$\bar{n}_S = \{\ \cos\ A\ \sin\ i,\ \sin\ A\ \sin\ i,\ \cos\ i\ \} \tag{5}$$

$$\bar{n}_Z = \{\ 0,\ 0,\ 1\ \}$$



a = phase angle
i = angle of incidence
e = angle of emission
A = azimuthal angle
P = center of crater at arbitrary position on planetary surface

R = crater radius
h = crater depth
z = normal to planetary surface
x = directed to the observer

Figure 4.4-3 . Geometry of a crater of radius **R** and depth h at an arbitrary point **P**.

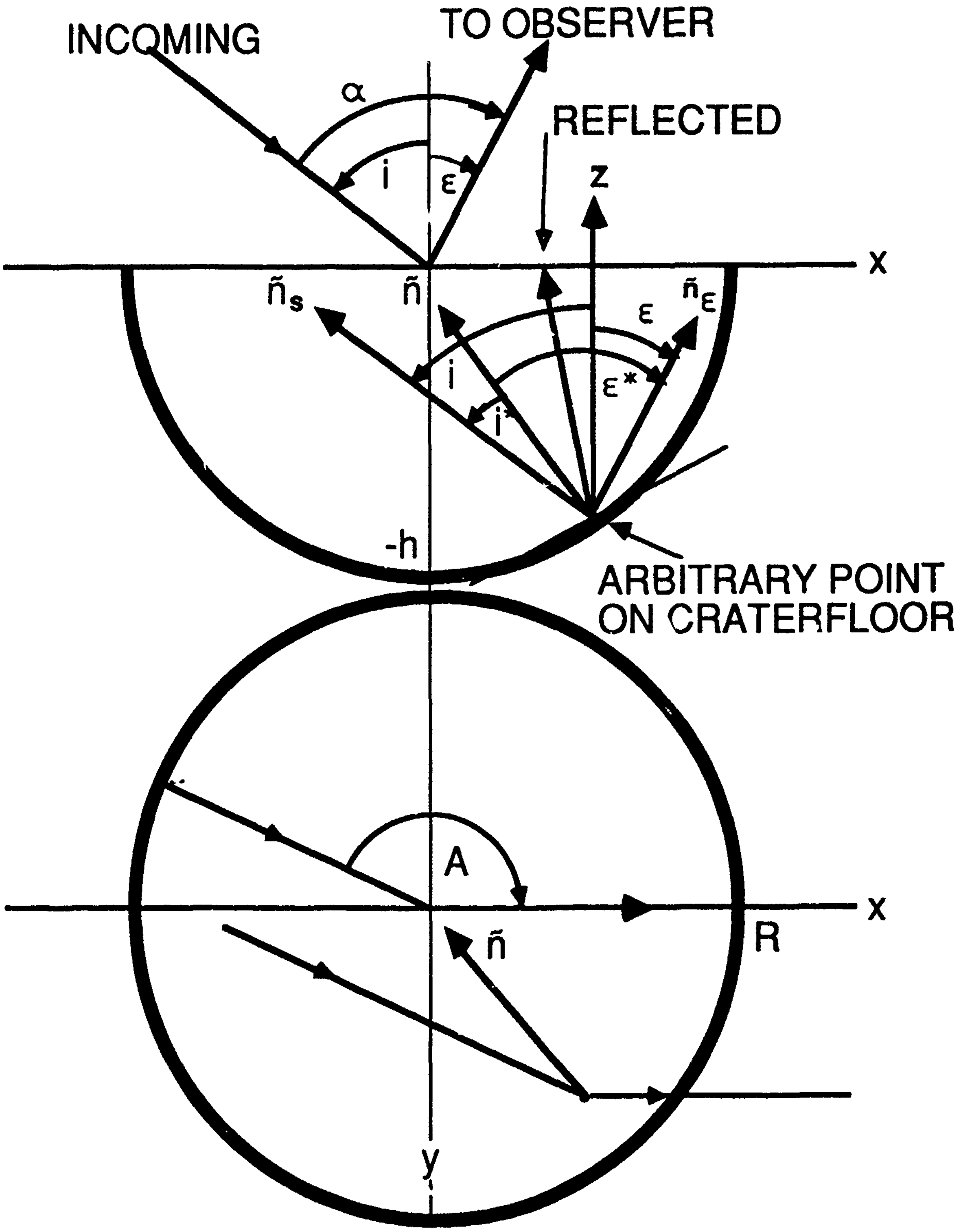


Figure 4.4-4 Illumination and observation geometry at a point inside the crater

The cosines of the angles of incidence and emission at any point inside the crater are,

$$\cos i^* = \bar{n}_S \cdot \bar{n} = \frac{\cos i - 2h / R^2 \sin i \{x \cos A + y \sin A\}}{\{1 + [4h^2 / R^2](x^2 + y^2)\}^{1/2}} \quad (6)$$

$$\cos e^* = \bar{n}_E \cdot \bar{n} = \frac{\cos e - [2h / R^2] x \sin e}{\{1 + [4h^2 / R^2](x^2 + y^2)\}^{1/2}} \quad (7)$$

Figure 4.4-4 shows the illumination and observation geometry at a point inside the crater. Figure 4.4-5 gives examples of the model crater patterns illumination and what the observer sees for a typical viewing orientation, projected into the x-y plane.

The above geometrical description is the first part of a program being written in Fortran V which is run on the University of Wyoming Cyber-760 computer. The model divides the crater surface into 516 segments of roughly equal area which behave as gray bodies. We then set up and solve a 1-dimensional heat flow equation for each segment employing the method used in the two-albedo "golf ball" model done previously. Solution of the heat-flow equation results in a temperature map on the crater surface. From the temperature map we can calculate the emergent flux from the crater and compare it to the incident flux, thus allowing us to look at crater emission in some detail. Assuming that each crater segment radiates into 2 π steradians of open sky as in the "golf ball" model would significantly overestimate the flux from the crater, as the points inside the crater radiate in to much less the 2π-steradians. Multiple scattering is significant for objects with albedo greater the 0.6 (Buratti, Veverka 1985), whereas it can be neglected for objects with an albedo much less than ~0.6. Currently we are devising a method that will account for crater segment radiating into less than 2π-steradians. We are also looking into a method of including multiple scattering for objects with high albedo.

Matson, D., L., Johnson, T., V., Veeder, G., J. and Nelson, R., M.: 1983, "Mysteries of the Galilean Satellites Brightness Temperatures, *BAAS Vol. 15*, p.852.
Murcray, F., H.: 1965, *JGR VOL. 70*, p.4959.
Matson, D., L.: 1971, California Institute of Technology, Ph. D. Thesis.
Hameen-Anttila,et al.,:1965
Buratti, VeVerka,:1985

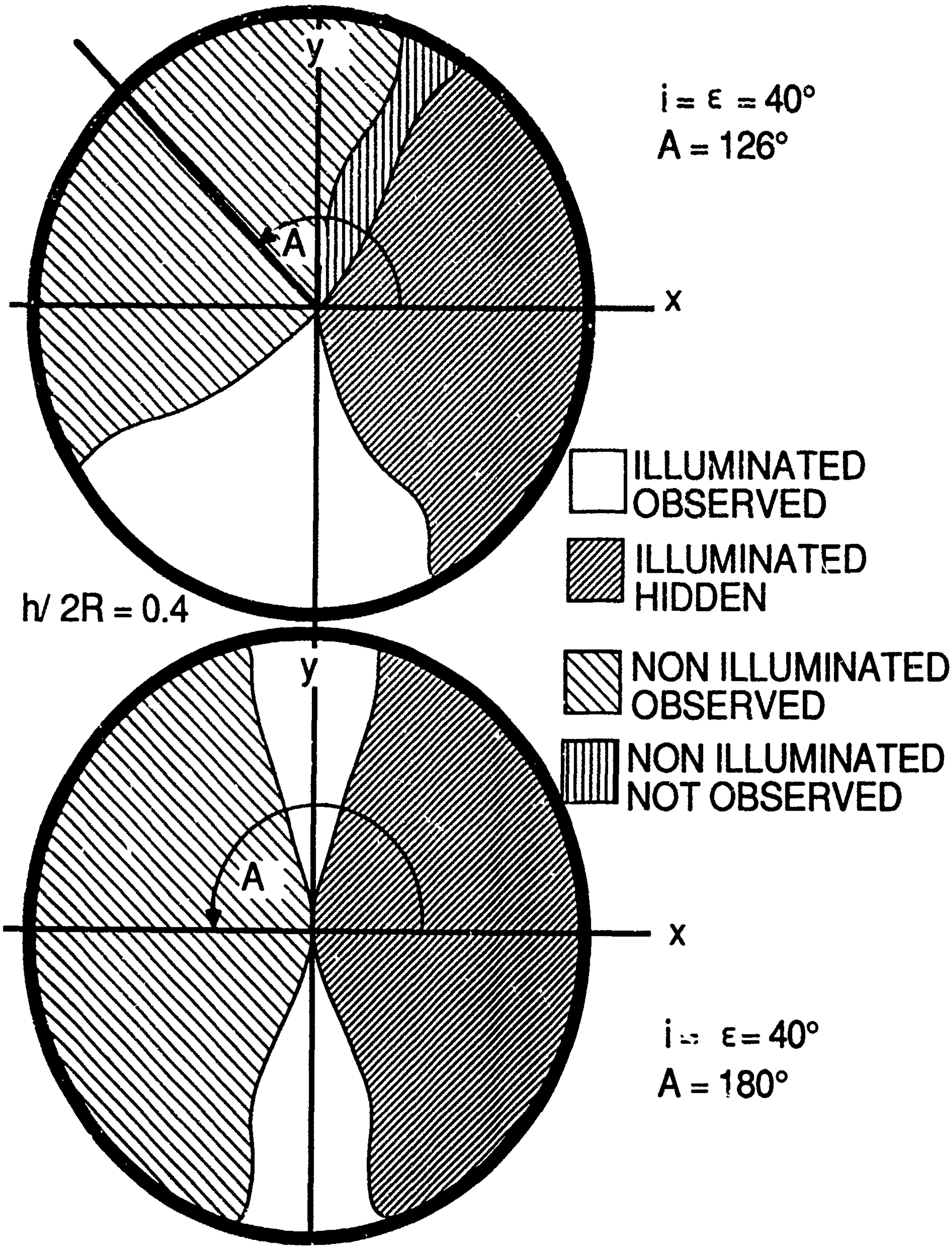


Figure 4.4-5 Typical illumination and observation coverage in the XY plane as described by the equations.

5.0 APPENDICES

Several items are included in the Appendices: (5.1) the report submitted by Frank Lander for his Masters degree and (5.2) the operating manual for the Infrared Laboratories Inc., for Silicon Bolometer # 1059, (5.3) Research Conducted at the Lunar and Planetary Institute by Karl Vogler, (5.4) A paper submitted to *Icarus*, Modeling the Non-Gray-Body Thermal Emission from the Full Moon, (5.5) Surface Roughness and Infrared Emission from Solid-Surfaced Planetary Bodies, a Ph.D. thesis proposal by Karl Vogler, (5.6) Description of the ADC-1 data acquisition and control peripheral and (5.7) Description of the RTD Resistance Temperature Device, and (5.8) some miscellaneous articles.

5.1 Report: Chopper and Automated Telescope (46 pages).

5.2 The Silicon Bolometer Operating Manual (53 pages).

5.3 Research Conducted at the Lunar and Planetary Institute.

5.4 Modeling the Non-Gray-Body Thermal Emission from the Full Moon.

5.5 Surface Roughness and Infrared Emission from Solid-Surfaced Planetary Bodies.

5.6 The ADC-1 data acquisition and control peripheral (1page).

5.7 The RTD Resistance Temperature Device.(3 pages).

5.8 Articles